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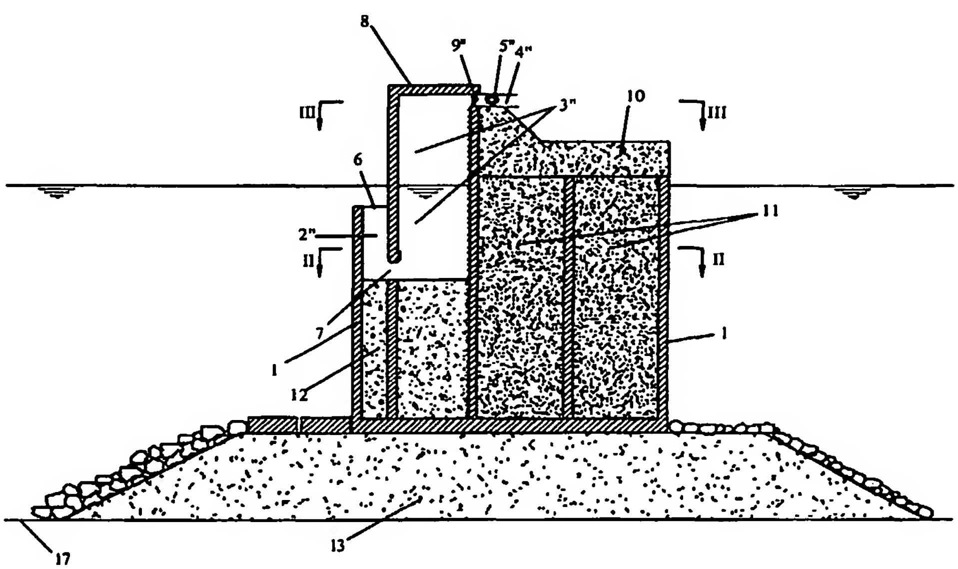
(54) Title: OSCILLATING WATER COLUMN WAVE ENERGY CONVERTER INCORPORATED INTO CAISSON BREAKWATER.



(57) Abstract: A caisson breakwater provided with vertical duct 2'', room 3'', air-duct 4'', self-rectifying turbine 5''. Under the fluctuations of wave pressure on the outer opening 6, the water, alternately, enters and exits, so that the air in room 3'', alternately, is compressed and expands, and an alternate air flow is produced in the air-duct 4''. The vertical duct 2'' and the room 3'' form a U-conduit, and the air in the room 3'' acts as a spring. The eigenperiod of oscillations in said U-conduit grows as the width of the vertical duct 2'' is reduced and/or the length of said vertical duct is increased, and/or the width and height of the room 3'' is increased. The eigenperiod is fixed close to the wave period of the waves which convey the largest amount of wave energy in a year, so as to absorb a very large quantity of wave energy.

OSCILLATING WATER COLUMN WAVE ENERGY CONVERTER INCORPORATED INTO CAISSON BREAKWATER

Technical field

The invention discloses a caisson breakwater which is able to protect a port or a marine sheet of water with a small wave reflection, and is able to convert wave energy into electric power.

Background art

Caisson breakwaters (see e.g. Goda Y., Random Seas and Design of Maritime Structures, World Scientific, chap. 4, 2000; or Boccotti P., Wave Mechanics for Ocean Engineering, Elsevier, chap. 13, 2000) consist of caissons in reinforced concrete close to each other or linked together, on a foundation on the seabed. Each caisson is subdivided into a number of cells by vertical walls. Typically the caissons are manufactured in dry docks, towed and sunk. The cells are filled with sand and/or gravel and/or concrete or other kind of ballast. Then a superstructure is cast in concrete.

Caisson breakwaters are excellent for protecting ports, because they can be built easily and are very resistant. The only flaw is that they reflect nearly all the incident wave energy, and, as a consequence, wave heights off the breakwater grow, and huge overtopping discharges occur. Of course, the wave amplification may be dangerous for boats and ships approaching a port, and the overtopping discharge may be dangerous for persons, facilities, and boats inside a port.

US patent 6,450,732 B1 has disclosed a submerged caisson on the seabed, with an air pocket and a vertical duct having the same width as the caisson. The upper opening of the vertical duct is beneath the sea level, and through this opening, the water alternately enters the caisson and exits from the caisson. The height of the air pocket inside the caisson is tuned with means for pumping or releasing air. Tuning is made so that the eigenperiod of free oscillations inside the caisson be close to the wave period. An embodiment of patent US 6,450,732 B1 comprises a self-rectifying turbine (e.g. a Wells turbine) that is a turbine whose direction of rotation does not change if the flow is reversed. This turbine is in a small section of the

vertical duct and is driven by the high-speed water-flow in said duct.

The plant disclosed by US Patent 6,450,732 B1 is an excellent absorber of wave energy, and it can be used very well to build submerged breakwaters with a very low environmental impact. These breakwaters are able to protect beaches from erosion, but they cannot protect a port because a part of the wave energy goes beyond these breakwaters. Moreover, the caisson of US Patent 6,450,732 B1, having an air pocket in pressure, needs a compressor, and needs control against air leakage. As a wave energy converter the caisson of US Patent 6,450,732 B1 has the turbine beneath the sea level, which implies some difficulty of maintenance and the need for a water-tight room for a generator.

Conventional wave energy converters known as OWCs (oscillating water columns) are widely described in the scientific literature. They may be coastline OWCs (see U.S. patent 5191225), breakwater OWCs (see Takahashi S. et al., Proc. 23rd Int. Conf. On Coastal Eng., 3440-3453, Amer. Soc. Civil Engineers, New York, 1992), or floating OWCs (see U.S. patent 6194791), according to whether they are installed on a coast, or in a caisson breakwater, or in a sinking structure. OWCs, essentially, consist of a box which rests on the seabed, with the roof above the sea level and with a large vertical opening in the main vertical wall (the one beaten by waves). This vertical opening extends from nearly the seabed to nearly the sea level, so that waves be able to propagate into the OWC. The air between the sea surface and the roof of the box, alternately, is compressed and expands because of the waves on the sea surface. An air-duct connects the OWC to the atmosphere, and a self-rectifying turbine is driven by an alternate air flow in said air-duct.

Thus, unlike the absorption device of the present invention which we are going to present, an OWC is not a U-conduit with an air pocket acting as a spring. Hence, an OWC cannot exploit a natural resonance where the eigenperiod of free oscillations in a U-conduit is equal to the wave period. This is why for improving the efficiency, some OWCs exploit a forced resonance with some complex devices for phase control in each individual wave (see Korde U.A. Applied Ocean Res. 13, 1991).

Summarizing, OWCs call for a large vertical opening in the main vertical wall so that their structure differs deeply from the compact structure of conventional caisson breakwaters. Moreover, to improve the efficiency, OWCs need some complex devices for phase control.

The objectives of the present invention are to make a caisson breakwater which:

(i) is suitable to protect a port;

(ii) reflects only a small share of the incident wave energy, and converts wave energy into electric power;

(iii) has turbines above the sea level, does not need means such as compressors, and does not need control against air leakage;

(iv) has an absorption device consisting of a U-conduit with an air pocket acting as a spring;

(v) does not need complex devices for phase control, given that it exploits a natural resonance where the eigenperiod of oscillations in the U-conduit is close to the wave period;

(vi) has the same compact structure and well-established building trade as conventional caisson breakwaters.

Disclosure of the invention

The objectives of the invention are obtained with a caisson breakwater whose caissons are made as shown in Fig.1. Specifically, a caisson 1 comprises:

(i) a vertical duct 2 which extends substantially along the whole caisson 1 and is connected with the sea through an upper opening 6;

(ii) a room 3 which extends substantially along the whole caisson and is connected with the vertical duct 2 through an opening 7; the base of said room 3 being beneath the sea level, and the roof 8 of said room 3 being above the sea level;

(iii) an air-duct 4 connecting the room 3 with the atmosphere;

(iv) a self-rectifying turbine 5 in the air-duct.

The vertical duct 2 and the room 3 form a U-conduit wherein the air in the room 3 acts as a spring. The eigenperiod of oscillations in this U-conduit grows as:

(i) the width of the vertical duct 2 is reduced,

(ii) the length of the vertical duct 2 is increased,

(iii) the width and height of the room 3 is increased,

(iv) the diameter of the air-duct 4 is increased.

The width and the length of the vertical duct 2, and the width and the height of the room 3 are fixed so that the eigenperiod be close to the wave period of the waves which convey the largest amount of energy in the course of a year. As an example

basing ourselves on long-term wave statistics, we should fix an eigenperiod of about 6s for the plants in the Mediterranean Sea.

The plant of the present invention works as follows. Under wave action, pressure fluctuates on the outer opening 6 of the vertical duct 2. These pressure fluctuations cause oscillations of the water in the U-conduit which consists of the vertical duct 2 and the room 3. As a consequence the air in the room 3 is compressed and expands, and an alternate air flow is produced in air-duct 4. This air flow drives the self-rectifying turbine 5. Thus, waves do not propagate into the plant of the present invention, while, as said, waves propagate into OWCs.

Under resonance conditions, when the eingenperiod is close to the peak period of the wave spectrum of the sea state, we estimate that this plant is able to absorb up to the 80%÷90% of the incident wave energy, which means that the reflected wave energy is reduced to only the 10%÷20% of the incident wave energy. This estimate has been done through numerical simulations of random wind-generated waves (see Boccotti P., Wave Mechanics for Ocean Engineering, 2000, caps. 4 and 8).

As for the control, one must check that the water in the room 3 does not impact the roof 8. This event could occur in some extreme storm. When the water level in the room 3 exceeds some safety threshold, valve 9 must be closed. The water level in the room 3 may be measured by means of an ultrasonic probe attached to the roof 8.

Given that the plant exploits a natural resonance there is no need at all for phase control. Finally, given that the average air pressure in the room 3 is equal to the atmospheric pressure, there is no need for control against air leakage, nor there is need for compressors.

Given that the plant exploits a natural resonance in a U-conduit, it needs only a relatively small horizontal-outer-opening 6. Moreover, the U-conduit (that is the vertical duct 2 and the room 3) can be well above the base of the caisson 1, so that we can fill the room beneath the U-conduit with concrete. That is why the caisson breakwater of the present invention has nearly the same compact structure as a conventional caisson breakwater.

Brief description of drawings

The present invention will now be described for illustrative and not limitative purposes, with reference to the drawings in which:

Fig. 2 is a vertical cross-section of a first embodiment of a caisson of the

breakwater according to the present invention, along plane I-I of Figs. 3 and 4;

Fig. 3 is a horizontal cross-section of the first embodiment of the present invention, along plane II-II of Fig.2;

Fig. 4 is a horizontal cross-section of the first embodiment of the present invention, along plane III-III of Fig.2;

Fig. 5 is a vertical cross-section of a second embodiment of the present invention, along plane I-I of Figs.6 and 7;

Fig. 6 is a horizontal cross-section of the second embodiment of the present invention, along plane II-II of Fig.5;

Fig. 7 is a horizontal cross-section of the second embodiment of the present invention, along plane III-III of Fig.5;

Fig. 8 is a vertical cross-section of a third embodiment of the present invention, along plane I-I of Figs.9 and 10;

Fig. 9 is a horizontal cross-section of the third embodiment of the present invention, along plane II-II of Fig.8;

Fig. 10 is a horizontal cross-section of the third embodiment of the present invention, along plane III-III of Fig.8;

Fig. 11 is a vertical cross-section of a fourth embodiment;

Fig. 12 is a vertical cross-section of a fifth embodiment.

Best way of carrying out the invention

The breakwater of the present invention consists of caissons close to each other or joined together, like a conventional caisson breakwater. Like caissons of a conventional caisson breakwater, the caissons of the breakwater of the present invention (see Figs. from 2 to 12) typically rest on a rubble mound foundation 13 on the seabed 17, and a caisson 1 of the breakwater consists of cells which are filled with sand and/or gravel 11 and/or concrete 12. Like in a conventional caisson breakwater, a superstructure 10 is cast in concrete above each caisson.

In a first embodiment (Figs. 2-3-4), some vertical stiffening-walls 14',14'' subdivide the vertical duct into sections 2',2'',2''', and subdivide the room 3 into cells 3',3'',3'''. Each of said cells 3',3'',3''' is connected with the atmosphere by its own air-duct 4',4'',4''' with self-rectifying turbines (e.g. Wells turbines) 5',5'',5''' and valves 9',9'',9'''.

In a second embodiment (Figs. 5-6-7), the vertical walls 14',14'',14^{IV},14^{V} are

provided with openings 15',15'', 15^{IV},15^{V}, near roof 8. Said openings let air flow from one to another of cells 3',3'',3''' and from one to another of cells 3^{IV},3^{V},3^{VI}. The cells 3',3'',3''', are connected with the atmosphere through air-duct 4' with self-rectifying turbine 5' and valve 9'; the cells 3^{IV},3^{V},3^{VI} are connected with the atmosphere through air-duct 4'' with self-rectifying turbine 5'' (not seen) and valve 9'' (not seen).

In a third embodiment (Figs. 8-9-10), there are no openings in the vertical walls 14',14'',14''',14^{IV},14^{V} and the cells 3',3'',3''' are connected with the air-duct 4' through tubes 16',16'',16''' being provided with valves 9',9'',9''', and the cells 3^{IV},3^{V},3^{VI} are connected with air-duct 4'' through tubes 16^{IV},16^{V},16^{VI} being provided with valves 9^{IV},9^{V},9^{VI}. The air-ducts 4' and 4'' are connected with the atmosphere, and contain self-rectifying turbines 5',5''.

A fourth embodiment is a more sophisticated version of the second embodiment, wherein there is a vertical septum which extends in height from the roof 8 downwards without reaching the base of the room 3. Closing the valve 9' in the air duct 4', the eigenperiod is reduced so that there is an increase of the production of electric power with wind waves of relatively small period.

In alternative (Fig. 12), in all the embodiments, the vertical duct 2 may be connected with the room 3 through a horizontal or sloping duct 19. The insertion of said horizontal or sloping duct 19 leads to an increase of the eigenperiod.

In the Oceans where the energy flux of waves is an order of magnitude greater than in the Mediterranean Sea, the breakwater of the present invention may be built for the only scope of producing electric power (not to protect a port).

A factory of green energy may consist of a caisson breakwater according to the present invention and a number of wind mills in the protected water sheet behind said breakwater. A first advantage of this factory is to eliminate the wave trust on the offshore wind mills. A second advantage is that a more regular production can be obtained. Indeed, even when there is no wind, the factory can produce electric power, exploiting the energy of swells.

Industrial applicability

The caisson breakwater of the present invention has the same solid structure in reinforced concrete as a conventional caisson breakwater. Also the building trade is the same, and the overall size is nearly the same - typically, the width of a caisson

breakwater of the present invention proves to be about 5% greater than the width of a conventional caisson breakwater, under the same safety factors against sliding and overturning, and under the same load on the foundation. The hydraulic apparatus is particularly simple - typically, it consists of a single turbine per caisson, with a diameter between 1m and 1.5m. Control is reduced to a minimum, given that the plant exploits a natural resonance in a U-conduit and does not call for phase control.

Notwithstanding the overall simplicity, the breakwater of the present invention has two important advantages over a conventional caisson breakwater. First, it converts part of the incident wave energy into electric power. Second, it reflects less wave energy. Our computations, based on numerical simulations of random wind-generated waves with some characteristic spectra, show that the breakwater of the present invention is able to absorb more than the 70% of the incident wave energy per year, and is able to convert into electric power more than one third of the absorbed energy. For this estimate use has been made of the plots of Curran and Gato (Proc. Inst. Mech. Engrs. 211,1977) for the efficiency of a simple monoplane Wells turbine.

Claims

1 A caisson breakwater characterized in that at least one caisson (1) of said caisson breakwater comprises a vertical duct (2), a room (3), and at least one air duct (4) connecting said room (3) with the atmosphere; where: said vertical duct (2) is on the wave beaten side of said caisson (1); said vertical duct (2) extends substantially along the whole caisson (1); said vertical duct (2) is connected with the sea through an upper opening (6) beneath the sea level; said vertical duct (2) is connected with the room (3) through a lower opening (7) or through a horizontal or sloping duct (19); said room (3) extends substantially along the whole caisson (1); said room (3) is in part beneath the sea level and in part above the sea level; said air duct, or air ducts, (4) comprises at least one turbine (5).

2 The caisson breakwater according to claim 1, where the vertical duct (2) is subdivided into sections (2',2'',2''') and the room (3) is subdivided into cells (3',3'',3''') by vertical walls (14',14''), and where each of said cells (3',3'',3''') is connected with the atmosphere through at least one air duct (4',4'',4''') with a turbine (5',5'',5'''), and where the air ducts (4',4'',4''') are provided with valves (9',9'',9''') or other closing devices.

3 The caisson breakwater according to claim 1, where the vertical duct (2) is subdivided into sections ($2',2'',2''',2^{IV},2^{V},2^{VI}$) and the room (3) is subdivided into cells ($3',3'',3''',3^{IV},3^{V},3^{VI}$) by vertical walls ($14', 14'',14''', 14^{IV}, 14^{V}$), where the air can circulate through the cells ($3',3'',3''',3^{IV},3^{V},3^{VI}$) or through groups or said cells, for example through openings ($15', 15'',15^{IV},15^{V}$) in the walls ($14', 14'',14''',14^{IV}, 14^{V}$), and the air in the cells ($3',3'',3''',3^{IV},3^{V},3^{VI}$) is connected with the atmosphere through at least one air-duct (4',4'') being provided with turbines (5',5'') and valves (9',9'') or other closing devices.

4 The caisson breakwater according to claim 1, where the vertical duct (2) is subdivided into sections ($2',2'',2''',2^{IV},2^{V},2^{VI}$) and the room (3) is subdivided into cells ($3',3'',3''',3^{IV},3^{V},3^{VI}$) by vertical walls ($14',14'',14''',14^{IV},14^{V}$), with the cells ($3',3'',3''',3^{IV},3^{V},3^{VI}$) being connected with the atmosphere through tubes ($16',16'',16''',16^{IV},16^{V},16^{VI}$) which join (directly or with some interposed distribution frames) at least one air-duct (4',4'') being provided with turbines (5',5''), and where the tubes ($16',16'',16''',16^{IV},16^{V},16^{VI}$) are provided with valves

($9', 9'', 9''', 9^{IV}, 9^{V}, 9^{VI}$) or other closing devices.

5 The caisson breakwater according to claim 2 wherein the room (3) is provided with a vertical septum (18), and where said septum (18) extends for all the width of the room (3) and extends in height from the roof (8) downwards without reaching the base of said room (3).

6 A factory of green power, characterized in that said factory consists of the caisson breakwater according to claims 1 or 2 or 3 or 4 or 5, and a number of wind mills in the protected water-sheet behind said caisson breakwater.

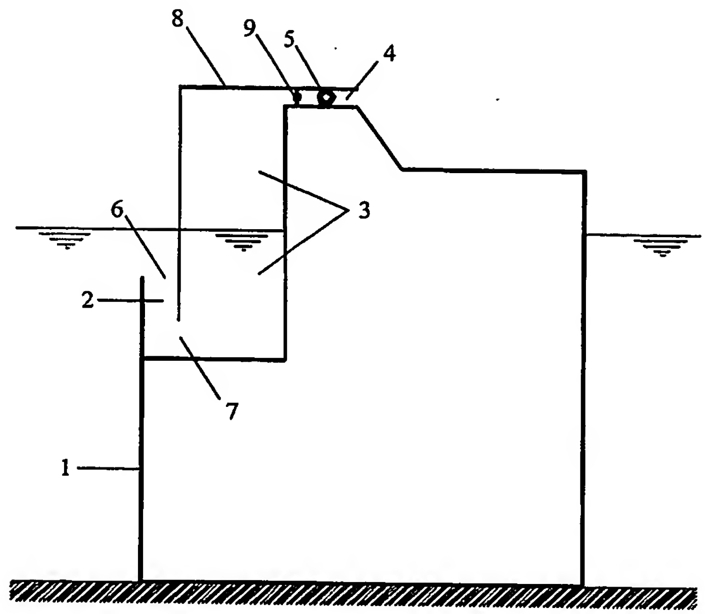


Fig. 1

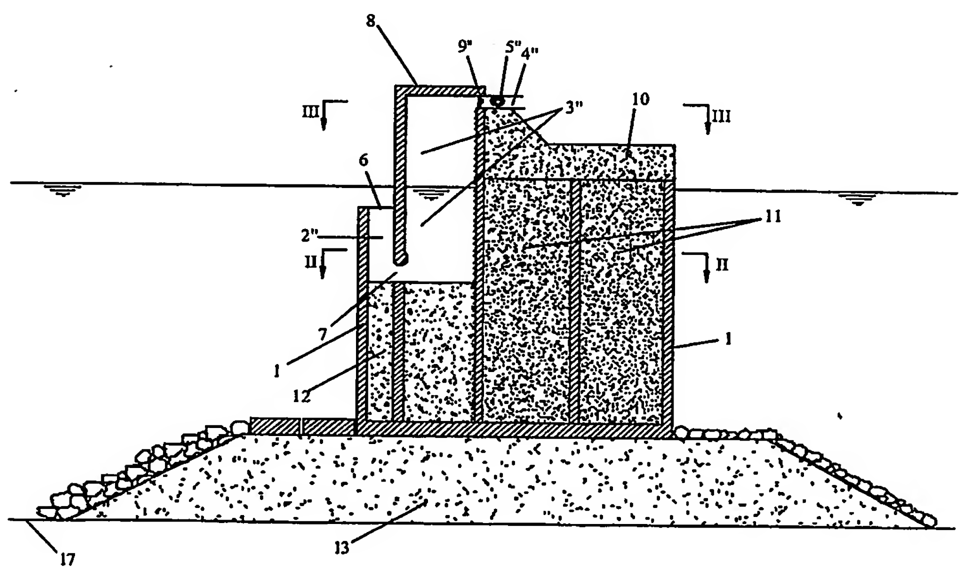


Fig. 2

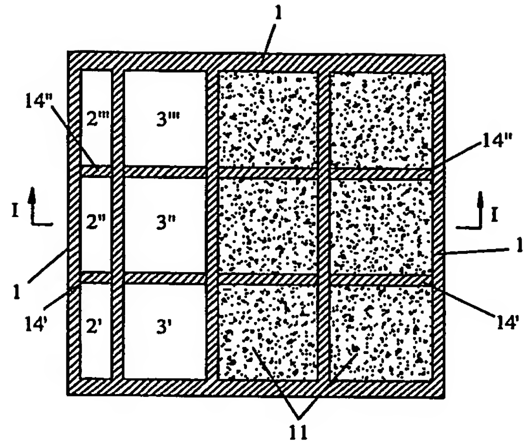


Fig. 3

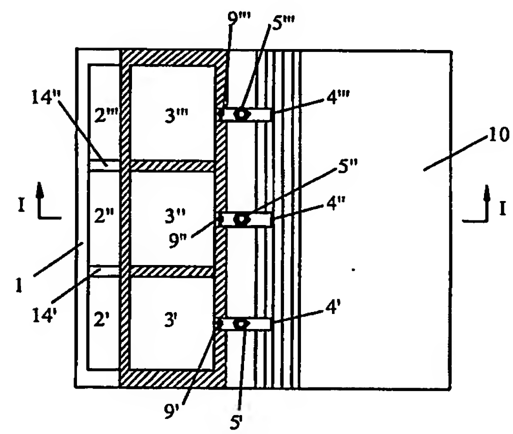


Fig. 4

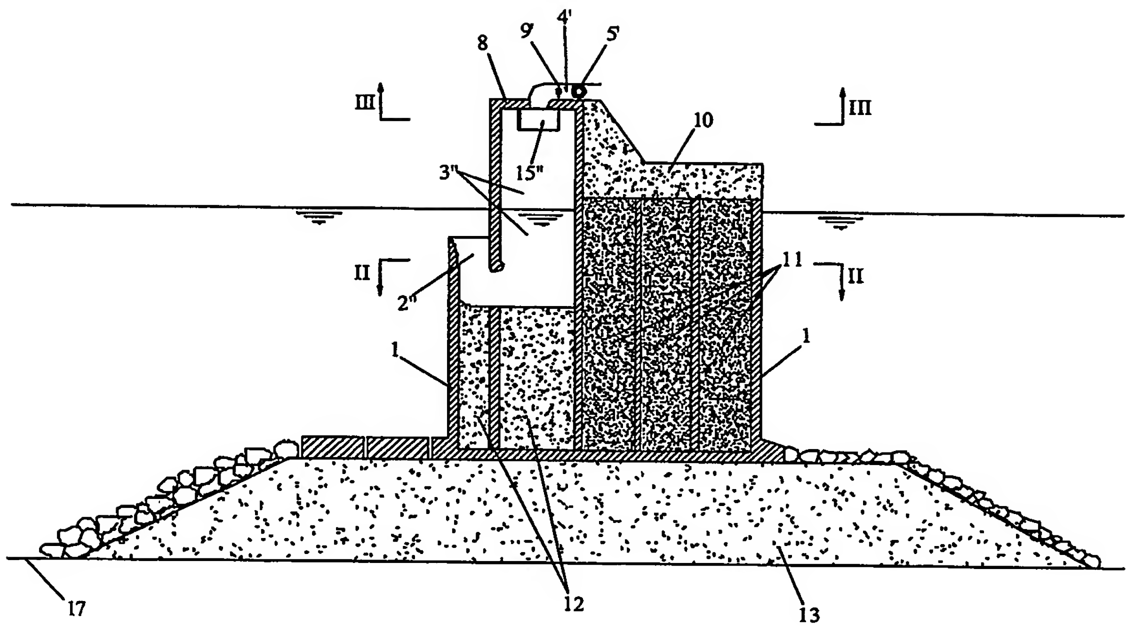


Fig.5

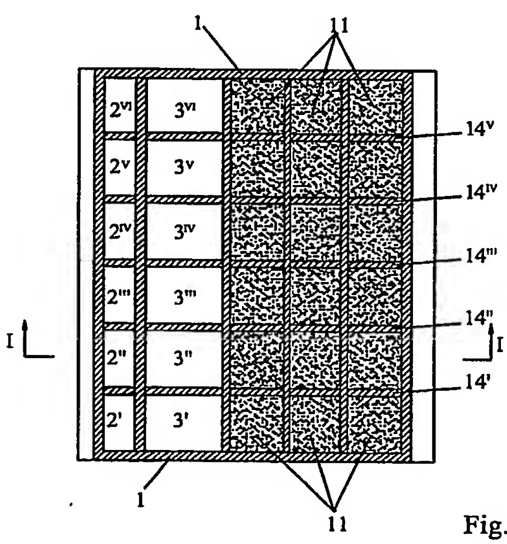


Fig.6

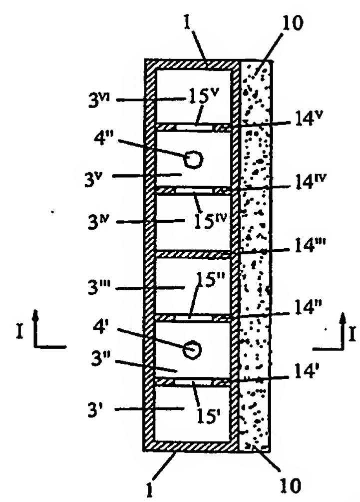


Fig.7

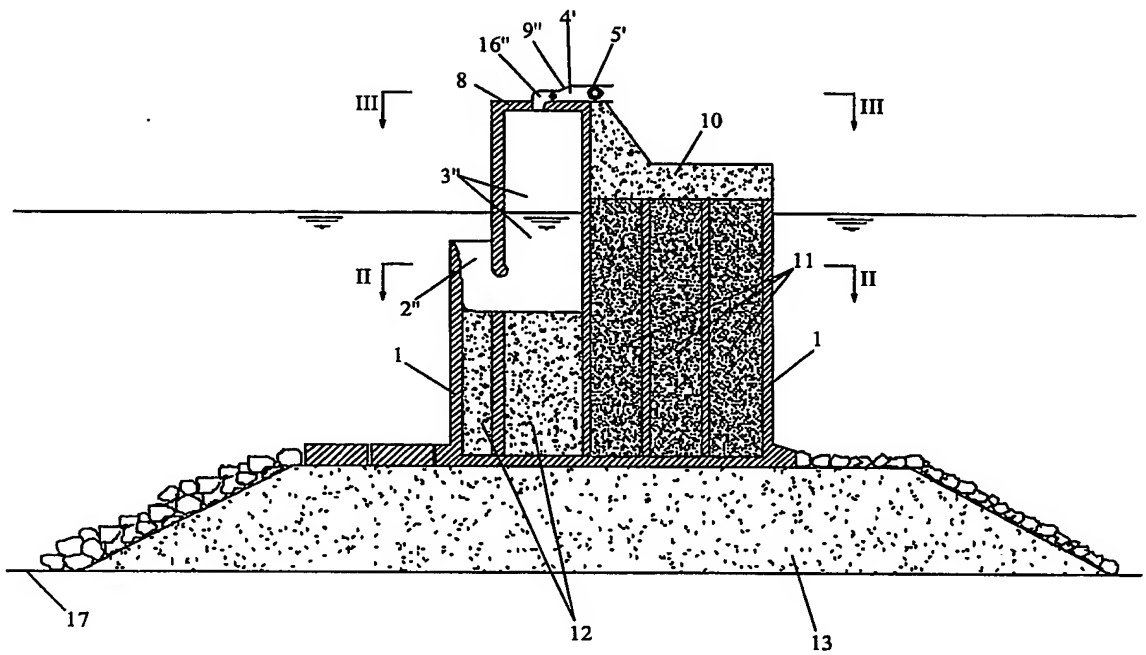


Fig.8

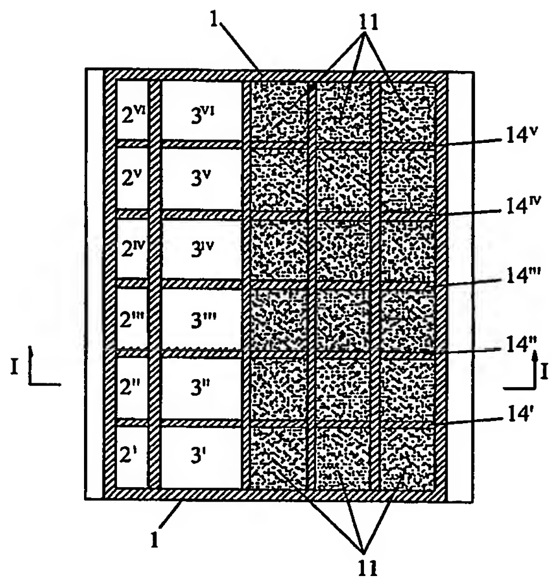

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Fig. 9

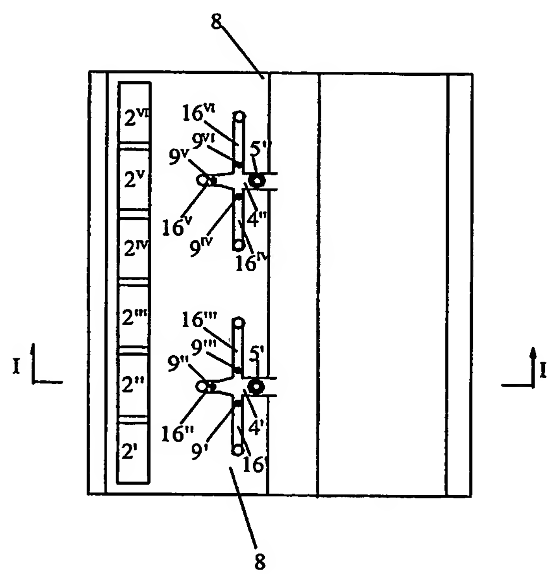
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Fig. 10

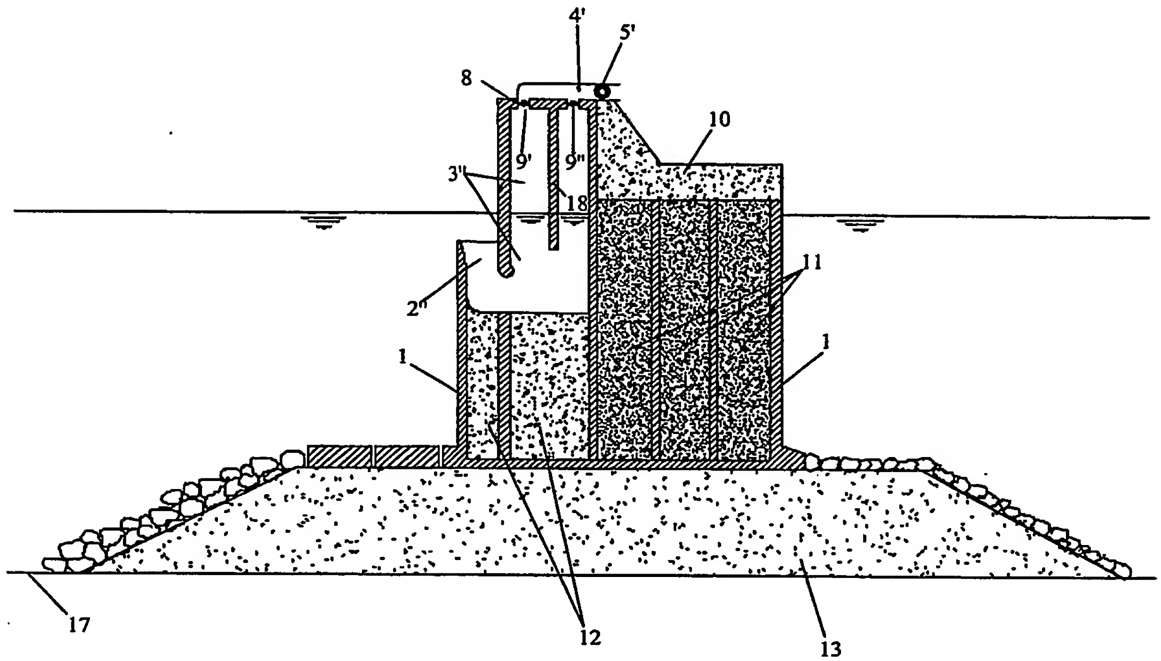

Fig.11

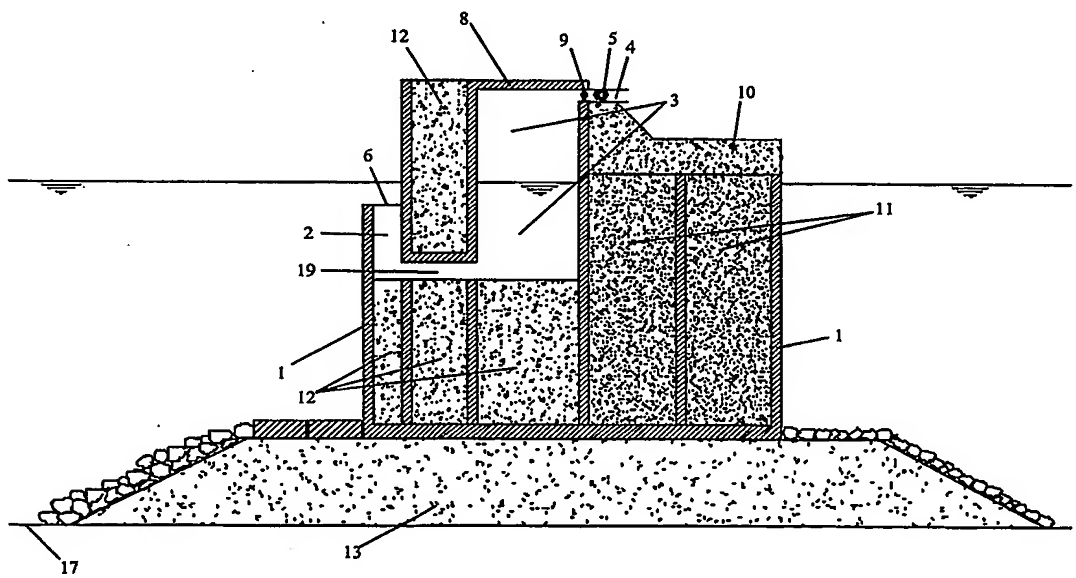

Fig.12